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## PERFORMANCE OF PIEZORESISTIVE AND PIEZOELECTRIC SENSORS IN PULSED REACTOR EXPERIMENTS

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### ABSTRACT

Pulsed reactor-based experiments require radiation tolerant sensors that do not perturb the device under test, or allow a radiation-induced signal to mask the true sensor output. Several commercial off-the-shelf accelerometers, pressure transducers, and acoustic emission sensors were subjected to multiple high-power reactor pulses. A piezoresistive accelerometer capable of operation to at least 44 kGy and  $8.7 \times 10^{15}$  n/cm<sup>2</sup> is identified, and a piezoresistive pressure transducer that is resistant to about half that radiation level is selected. Further, two piezoelectric acoustic emission sensors employing lead metaniobate are also found to function to 55 kGy and  $1.1 \times 10^{16}$  n/cm<sup>2</sup>.

### 1. INTRODUCTION

Prompted by the unexpected failure of piezoresistive (PR) sensors in both an elevated gamma-ray environment and reactor core pulse tests, we initiated radiation testing of several microelectromechanical systems (MEMS) accelerometers and pressure transducers to ascertain their radiation hardness. In addition, piezoelectric (PE) accelerometers and acoustic emission sensors were tested. Such instrumentation is attractive to reactor experiments due to their small size and broad range of frequency response. The overall goal of this study is to assess the usefulness of commercial PR and PE sensors for experiments, especially shock testing, taking place in a pulsed reactor core.

### 2. BACKGROUND

Although researchers have noted there is little scientific literature on radiation effects in MEMS, scientists are already touting their use in radiation environments based on extending an understanding of radiation effects on semiconductor devices to MEMS. Knudson *et al.* (1996), Lee *et al.* (1996), and Edmonds *et al.* (1998) describe radiation testing of capacitance-type MEMS accelerometers. Boyadzhyan and Choma (1998) re-

port on a tunneling accelerometer that was unaffected by a 1-kGy gamma dose. Zhu *et al.* (2001) fabricated one polycrystalline and two silicon-on-insulator piezoresistive pressure sensors. They found that a gamma dose of 23 kGy caused a slight shift (~ a few mV) in the offset voltages of the three sensors, but no degeneration of linearity or sensitivity.

Because of the limited literature concerning radiation testing of MEMS devices, literature regarding testing of piezoresistive sensors in general (not specifically MEMS) was sought. The findings within the literature are summarized in Table 1. Bouche (1970), Thomas (1973), and Bierney (1976) discuss the design of PR and PE accelerometers for operation in nuclear reactor environments. Thomas (1973) states that heavily doped gages are far more resistant to reactor radiation effects since the radiation damage mechanism involves changes in the crystalline lattice structure.

**Table 1** Piezoresistive sensor radiation testing results in the literature.

Sensor Type	Radiation Exposure	Key Findings	Reference
Semiconductor strain-gage pressure transducers	$10^{15}$ n/cm <sup>2</sup> and 10 kGy(C) of gamma	Less than 1% change in sensitivity	Terry <i>et al.</i> (1965)
Piezoresistive accelerometers	$6 \times 10^{15}$ n/cm <sup>2</sup> and 3 MGy(C) gamma	Satisfactory dynamic performance; significant changes in unstrained resistance	Chapin <i>et al.</i> (1966)
Piezoresistive accelerometers (18)	$5 \times 10^{15}$ n/cm <sup>2</sup> in TRIGA reactor	Satisfactory operation; negligible to drastic change in strain resistance	Langdon <i>et al.</i> (1970)
Polysilicon and SOI pressure sensors	<sup>60</sup> Co $\gamma$ -rays; dose of 23 kGy(H <sub>2</sub> O)	Sensitivity and linearity did not degenerate; offset voltage shift	Zhu <i>et al.</i> (2001)

Scientific literature (Bouche, 1970; Thomas, 1973; Bierney, 1976; Broomfield, 1985) reports various instances in which piezoelectric transducers and materials have been radiation tested. Thomas (1973) states that long-term exposure of PE material to moderate flux levels primarily manifests itself as a sensitivity decrease; however, at high ionization rates, radiation-induced charge deposition can mask the PE charge generated by the measurand. Bouche and Lovelace (1970) note that measurable pyroelectric outputs may be produced if significant heating were to occur from burst radiation such as that of a weapons testing environment.

The radiation threshold for permanent damage of some pressure transducers constructed with barium titanate and lead zirconate titanate (PZT) are given in Table 2. Also given in Table 2 are the neutron fluxes which upset signals from those sensors. Rad hard PE sensors are available in the marketplace. For example, Endevco markets PE accelerometers for the nuclear power industry using materials termed PIEZITE® P-8 and P-14. Accelerometers constructed with P-8, which is a PZT composition, are rated to a gamma dose of 100 kGy and a neutron fluence of  $10^{10}$  n/cm<sup>2</sup> and a service temperature of 288°C. Those models employing P-14, which is a proprietary material described as a ferroelectric, hard (polycrystalline) ceramic, are rated to a gamma dose of  $6.2 \times 10^8$  Gy and a neutron fluence of  $3.7 \times 10^{18}$  n/cm<sup>2</sup>, and a sensor operating temperature of 400°C to

480°C. Thomas (1973) and Bierney (1976) report that a P-18 (lithium niobate) based accelerometer remained within calibration limits when subjected to a combined 4 MGy gamma dose and  $3 \times 10^{18}$  n/cm<sup>2</sup> fluence; however, a PZT element transducer showed a 40% sensitivity decrease due to apparent depolarization of the material. To utilize PZT-5A in an acoustic emission, continuous monitoring system for long-term use for a nuclear reactor pressure vessel, Vetrano *et al.* (1972) employed a waveguide to locate the PE transducers and electronics away from the 315°C, high-radiation ( $\sim 10^5$  n/cm<sup>2</sup>·s) environment.

**Table 2** Radiation studies of PE pressure transducer (Holmes-Siedle and Adams, 2002).

Pressure Transducer Piezoelectric Material	Permanent Damage Threshold		Data Upset Threshold Flux
	Ionization	Bulk damage	
Barium titanate	95 kGy	$7.6 \times 10^{10}$ n/cm <sup>2</sup>	$2.1 \times 10^4$ n/cm <sup>2</sup> ·s
Lead zirconate titanate	400 MGy	$3.6 \times 10^{18}$ n/cm <sup>2</sup>	$1.2 \times 10^{12}$ n/cm <sup>2</sup> ·s

### 3. PULSED REACTOR TESTING AND RESULTS

Several piezoresistive MEMS and PE sensors were operated in the pulsed reactor environments of the Sandia Pulse Reactor (SPR-III) and/or the Annular Core Research Reactor (ACRR). The SPR-III, which has a 17.78-cm (diameter) central irradiation cavity, provides a unique, near-fission-spectrum radiation environment with each pulse having a nominal fluence of  $6.1 \times 10^{14}$  n/cm<sup>2</sup> and concomitant gamma dose of 1.7 kGy for an 11 MJ pulse; the ACRR is a pool-type reactor capable of delivering a neutron fluence of  $6.0 \times 10^{15}$  n/cm<sup>2</sup> and gamma dose of 30 kGy (3 Mrads) for each 300 MJ pulse (Choate, 1993). The seven reactor experiments, which were carried out over a four-year period, are summarized in Table 3. Each pulse within experiments 2, 3 and 4 was of nearly identical magnitude; the magnitudes of consecutive pulses in experiments 5, 6 and 7 were systematically increased from  $\sim 30$  to  $\sim 275$  MJ. None of the tested sensors is designed for radiation environments, rather they are commercial off-the-shelf (COTS) devices.

#### 3.1 Piezoresistive MEMS Sensor Performance

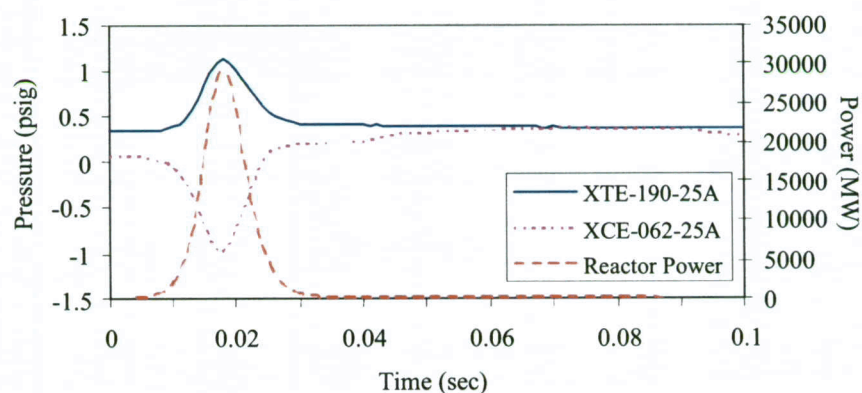
The piezoresistive sensors tested consist of three different Kulite Semiconductor Products, Inc. pressure transducers (models CT-190, XCE-062 and XTE-190) and two Endevco Corporation accelerometers (models 7264 and 7270A). These MEMS pressure transducers and accelerometers are micromachined silicon-on-insulator and bulk silicon devices, respectively. These sensors are small devices with the piezoresistive elements placed on 2 or 4 legs of a Wheatstone bridge. The pressure transducers employ an additional resistive network for temperature compensation whereas the accelerometers do not.

The pressure transducers received the greatest attention during this project with at least one pressure transducer tested in each of the seven experiments. The initial testing in the SPR-III provided a smaller ratio of gamma to neutron radiation as compared to the ACRR. An XCE-062 and an XTE-190 were subjected to four pulses from the SPR-III. In addition, a CT-190 (which is similar to the XTE-190, except that the CT-190 is designed for cryogenic applications) was exposed to a single SPR-III pulse. These three pressure transducers survived those reactor pulses without observable degradation.

Subsequently, further tests were conducted at the ACRR. Those additional experiments demonstrated another XTE-190 to survive seven pulses (tests 3 and 4); however, an XCE-062 exhibited anomalous behavior (see Fig. 1) from a single ACRR pulse. The main difference between the two sensors is their mass: the XCE-062 weighs 0.2 g whereas the XTE-190 weighs 4 g. Further exposure to a sustained gamma field resulted in complete failure of the XCE-062 sensor, whereas the XTE-190 continued to properly function, indicating that the XCE-062 is more gamma sensitive. Consequently, the XCE-062 was removed from further consideration.

**Table 3** Pulsed reactor testing of piezoresistive (PR) and piezoelectric (PE) sensors.

Test	Experiment Description	Total Exposure		Sensors (model number)
		Gamma (kGy)	Neutron (n/cm <sup>2</sup> )	
1	SPR-III (1 pulse)	1.7	$6.1 \times 10^{14}$	One MEMS PR pressure transducer (CT-190)
2	SPR-III (4 pulses)	6.8	$2.4 \times 10^{15}$	Two MEMS PR pressure transducers (Kulite XCE-062 and XTE-190)
3	ACRR (2 pulses)	18	$3.4 \times 10^{15}$	Two MEMS PR pressure transducers (XCE-062 and XTE-190); Two MEMS PR accelerometers (Endevco 7264C and 7270A)
4	ACRR (5 pulses)	44	$8.7 \times 10^{15}$	One MEMS PR pressure transducer (reused XTE-190); Two MEMS PR accelerometers (7264B); Two PE accelerometers (2255B-1)
5	ACRR (3 pulses)	37	$7.4 \times 10^{15}$	Two MEMS PR pressure transducers (XTE-190); Two PE acoustic emission sensors (B1025)
6	ACRR (4 pulses)	55	$1.1 \times 10^{16}$	Two MEMS PR pressure transducers (XTE-190); Two PE acoustic emission sensors (B1025)
7	ACRR (4 pulses)	55	$1.1 \times 10^{16}$	Two MEMS PR pressure transducers (XTE-190); Two PE acoustic emission sensors (B1080)

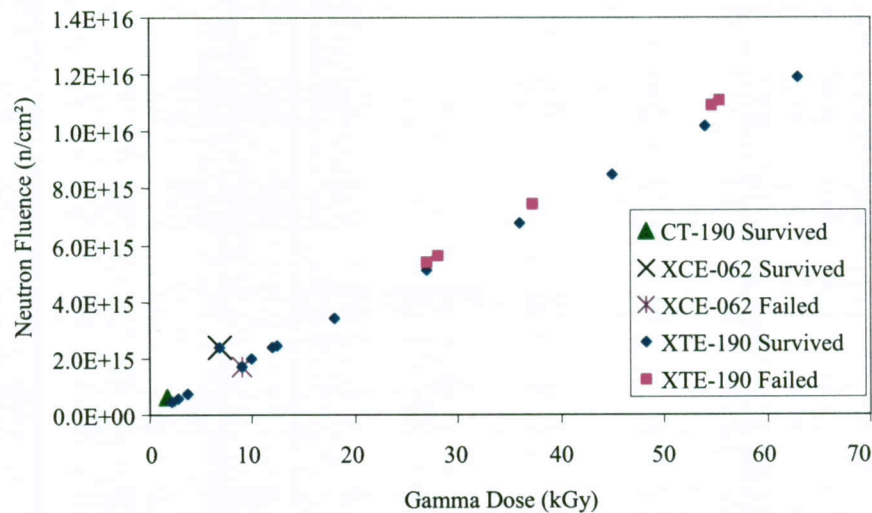


**Fig. 1** Kulite piezoresistive pressure transducer output after a 285 MJ ACRR pulse; the XCE-062 exhibits an anomalous output after the reactor pulse.

Six additional XTE-190 transducers were exposed to multiple ACRR pulses in the last three experiments, which showed that for total combined dose and fluence of more than 15 to 25 kGy and  $3 \times 10^{15}$  to  $5 \times 10^{15}$  n/cm<sup>2</sup>, respectively, that most sensor outputs

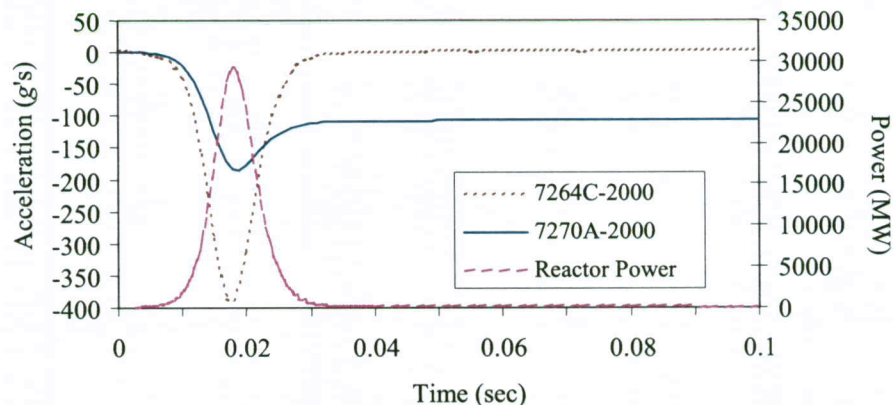


become erratic. Fig. 2 shows a summary of the pressure transducer performance from all seven experiments. This graph provides users with the capability to predict the survivability of a sensor for an expected dose and fluence in future reactor experiments.



**Fig. 2** Post reactor pulse performance of Kulite piezoresistive pressure transducers.

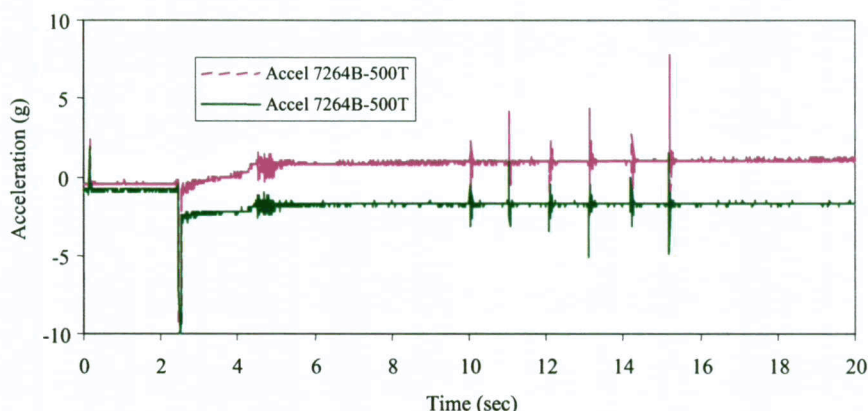
The MEMS accelerometers were subjected to pulses from the ACRR only. Fig. 3 shows that the sensors demonstrate a negative pulse coincident with the reactor pulse. The negative pulse is a radiation effect on the electronics versus a physical acceleration. The 7270A shows substantial bias immediately following exposure to a single ACRR pulse; therefore, it was eliminated for use in future pulsed reactor experiments. In contrast, during experiments 3 and 4, one Endevco 7264C and two 7264B accelerometers were exposed to two and five pulses, respectively, without any noticeable degradation. The 7264C is virtually identical to the 7264B, except that the seismic mass of the 7264C extends from the end of the sensor housing; the resulting difference is that the 7264B has a mounted resonance frequency of 28 kHz and a damping ratio of 0.005, whereas for the 7264C these specifications are 26 kHz and 0.05, respectively.



**Fig. 3** Endevco piezoresistive accelerometer output after a 285 MJ ACRR pulse; the 7270A exhibits a negatively biased output after the reactor pulse.

For experiment 4, a solenoid with a spring-loaded piston was mounted to the test package to perturb the accelerometers while they were in the reactor. Energizing or de-energizing the solenoid produced a single impulse. This arrangement allowed non-zero stimulation of the accelerometers, but the arrangement was subject to variability and the results should be viewed as qualitative in nature. Fig. 4 shows that one 7264B exhibits a slightly positive offset after the reactor shot, whereas the second 7264B shows a slightly negative offset. The output of each sensor rises a few g's over the 2.5 seconds after the reactor shot due to heating of the sensor. At about the 5-second mark, the increased noise output ( $\pm 2g$ ) of the sensors corresponds to the operation of the control rod chain drives.

Elsewhere (Holbert, 2003), we reported that for a pure gamma-ray exposure of tens of kGy, the XTE-190 pressure transducer and the 7264 accelerometer experience similar performance degradation: a drift in offset voltage with a slight increase in sensitivity. Catastrophic failure of the XTE-190 was observed at these radiation levels, but no such complete failure was ever seen in the 7264B/C.



**Fig. 4** Endevco 7264B piezoresistive accelerometer outputs following an 87 MJ ACRR pulse.

### 3.2 Piezoelectric Sensor Performance

The piezoelectric sensors tested included Endevco accelerometers (model 2255B-1) and two different Digital Wave Corporation acoustic emission (AE) sensors (models B1025 and B1080). PE accelerometers provide the highest frequency response; however, they are not capable of static (dc) response like piezoresistive sensors. The accelerometers and acoustic emission sensors employ the ferroelectric materials PIEZITE® and lead metaniobate, respectively. No prior radiation testing results were found for lead metaniobate. Both these PE materials are hard ceramics with relatively high Curie temperatures, which led us to hypothesize that they would be radiation resistant.

Two 2255B-1 accelerometers were subjected to five consecutive ACRR pulses in experiment 4, which systematically deteriorated the sensor outputs until the accelerometers completely failed from an  $8.7 \times 10^{15}$  n/cm<sup>2</sup> neutron fluence and 44 kGy gamma dose. The accelerometers included integral electronics (internal amplifier), which caused their demise. Noteworthy is that radiation-induced charge drove the output

from the PE accelerometers above 500 g; this might be expected when comparing against Table 2 since the peak ACRR flux and dose rate were  $2.5 \times 10^{16}$  n/cm<sup>2</sup>·s and 125 kGy/s, respectively, for each pulse.

The PE acoustic emission sensors, which have a sapphire face, are designed for modal acoustic emission measurements from 50 kHz to 2 MHz. The primary difference between the two sensors is their size. The B1080 has a volume about one-fifth of the B1025. Each AE sensor was connected to a 1 to 2 m 75-Ω coaxial cable, which was then connected to a charge preamplifier. The preamplifier was located away from the experimental package in order to reduce its radiation exposure. The six acoustic emission (AE) sensors did not have on-board electronics and functioned properly throughout the testing. AE data were acquired from each sensor during the two minutes immediately preceding and following each reactor pulse. The AE sensor outputs were the result of both radiation-induced charge and acoustic emissions in the test fixture. Each AE sensor was subjected to three or four pulses from the ACRR for a total exposure of around  $10^{16}$  n/cm<sup>2</sup> and 50 kGy. We find that these AE sensors are suitable for our applications.

#### 4. CONCLUSIONS

Various researchers have generally lauded the inherent radiation hardness of MEMS devices. We conclude that commercial piezoresistive MEMS and piezoelectric sensors are viable candidates for measurements in a pulsed reactor environment. We find the Kulite XTE-190 pressure transducer useable to a fluence and dose of  $4 \times 10^{15}$  n/cm<sup>2</sup> and 20 kGy, respectively. The Endevco 7264 accelerometers operate to a radiation exposure of more than twice the XTE-190. Finally, the Digital Wave B1025 and B1080 acoustic emission sensors function to even higher radiation levels although it is unclear as to the extent that the output signal is masked by the radiation-induced charge.

#### REFERENCES

- Choate, L.M., Schmidt, T.R., editors, Sandia National Laboratories Radiation Facilities, Technical Report no. SAND92-2157, 5th edition, August 1993, pp. 4-13.
- Bierney, T.K. Instrumentation for the measurement of vibration in severe environments such as nuclear reactors. *Operation of Instruments in Adverse Environments 1976*, Institute of Physics Conference Series No. 34, 1977, J. Knight, Ed., pp. 103-116.
- Bouche, R.R., Lovelace, D.E. Accelerometer characteristics used in transient motion and nuclear applications. *AFSWC Symp. on Instrum. for Nuclear Weapons Effects Simulation*, Kirkland Air Force Base, Albuquerque, NM, March 1970.
- Bouche, R.R., 1970. Accelerometers for use in nuclear reactor components. Winter Annual Meeting of the AMSE, New York, December 1970, *Flow-Induced Vibration in Heat Exchangers*, pp. 36-41.
- Boyadzhyan, V., Choma Jr., J., 1998. High temperature, high reliability integrated hybrid packaging for radiation hardened spacecraft micromachined tunneling



- accelerometer. *Proc. IEEE International Workshop on Integrated Power Packaging*, Chicago, IL, Sept. 17-19, 1998, pp. 79-83.
- Broomfield, G.H. Effects of temperature and irradiation on piezoelectric acoustic transducers and materials. UKAEA report no. AERE-R 11942, Harwell, UK, 1985.
- Chapin, W.E., Drennan, J.E., Hamman, D.J. The effect of nuclear radiation on transducers. Battelle Memorial Institute, REIC report no. 43, TIC report no. 3, October 31, 1966, 126 pp.
- Edmonds, L.D., Swift, G.M., Lee, C.I., 1998. Radiation response of a MEMS accelerometers: an electrostatic force. *IEEE Trans. Nuc. Sci.* **45**, 2779-2788.
- Holbert, K.E., Nessel, J.A., McCready, S.S., Heger, A.S., Harlow, T.H., 2003. Response of piezoresistive MEMS accelerometers and pressure transducers to high gamma dose. *IEEE Trans. Nuc. Sci.* **50**, 1852-1859.
- Holmes-Siedle, A. Adams, L., 2002. *Handbook of Radiation Effects*, 2<sup>nd</sup> ed., Oxford University Press, pp. 350-353.
- Knudson, A.R., Buchner, S., McDonald, P., Stapor, W.J., Campbell, A.B., Grabowski, K.S., Knies, D.L., Lewis, S., Zhao, Y., 1996. The effects of radiation on MEMS accelerometers. *IEEE Trans. Nuc. Sci.* **43**, 3122-3126.
- Langdon, W.R., Bennett, W.K., Decker, W.T., Garland, W.E., 1970. Radiation effects on piezoresistive accelerometers. *IEEE Trans. Indust. Electron. Cont. Instrum.* **IECI-17**, 99-104.
- Lee, C.I., Johnston, A.H., Tang, W.C., Barnes, C.E., Lyke, J., 1996. Total dose effects on micromechanical systems (MEMS): accelerometers. *IEEE Trans. on Nuc. Sci.* **43**, 3127-3132.
- Terry, F.D., Kindred, R.L., Anderson, S.D. Transient nuclear radiation effects on transducer devices and electrical cables. Phillips Petroleum Company, Atomic Energy Division, IDO-17103, TID-4500, November 1965, 68 pp.
- Thomas, R.L. Vibration instrumentation for nuclear reactors. *Proc. Intern. Symp. Vibrat. Problems in Industry*, Keswick, Cumberland, UK, April 1973, paper no. 627.
- Vetrano, J.B., Jolly, W.D., Hutton, P.H. Continuous monitoring of nuclear reactor pressure vessels by acoustic emission techniques. *Advances in Electronics and Electron Physics*, Conference on Periodic Inspection of Pressure Vessels, May 9-11, 1972, pp. 221-226.
- Zhu, S.-Y., Huang, Y.-P., Wang, J., Li, A.-Z., Shen, S.-Q., Bao, M.-H., 2001. Total dose radiation effects of pressure sensors fabricated on Unibond-SOI materials. *Nuclear Science and Techniques* **12**, 209-214.